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Category-based attentional guidance can operate in parallel for multiple target objects

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Highlights

- Visual search can be guided by target object categories
- Category-based attentional selection can operate concurrently at several locations
- Exemplar-based target selection is faster than category-based selection

Abstract

The question whether the control of attention during visual search is always feature-based or can also be based on the category of objects remains unresolved. Here, we employed the N2pc component as an on-line marker for target selection processes to compare the efficiency of feature-based and category-based attentional guidance. Two successive displays containing pairs of real-world objects (line drawings of kitchen or clothing items) were separated by a 10 ms SOA. In Experiment 1, target objects were defined by their category. In Experiment 2, one specific visual object served as target (exemplar-based search). On different trials, targets appeared either in one or in both displays, and participants had to report the number of targets (one or two). Target N2pc components were larger and emerged earlier during exemplar-based search than during category-based search, demonstrating the superior efficiency of feature-based attentional guidance. On trials where target objects appeared in both displays, both targets elicited N2pc components that overlapped in time, suggesting that attention was allocated in parallel to these target objects. Critically, this was the case not only in the exemplar-based task, but also when targets were defined by their category. These results demonstrate that attention can be guided by object categories, and that this type of category-based attentional control can operate concurrently for multiple target objects.

Keywords: visual attention; attentional control; visual search; category search; event-related brain potentials; N2pc component In visual search, observers have to find target objects

that are defined by particular features and appear among other task-irrelevant distractor objects. The allocation of attention to candidate target objects during the search process is guided by mental representations of known target-defining features (attentional templates; e.g., Duncan & Humphreys, 1992; Olivers, Peters, Houtkamp, & Roelfsema, 2011). These target templates can be activated during the preparation for a particular search episode, and are assumed to bias attentional selection processes towards objects with template-matching features (Wolfe, 1994, 2007; Desimone & Duncan, 1995). There are many different types of search tasks where targets are defined by different sets of features. It is obvious that not all target attributes are equally capable in guiding attention (e.g., Wolfe & Horowitz, 2004). Simple visual features such as stimulus colour, shape, or orientation are effective guiding attributes. In contrast, it is often assumed that higher-level attributes such as an object's category are unable to contribute to the guidance of attention during visual search. In line with this hypothesis, several studies have demonstrated that search for category-defined targets is much less efficient than search for targets that are defined by specific visual features (e.g., Malcolm & Henderson, 2009; Yang & Zelinsky, 2009). However, there is also behavioural evidence that object categories can affect the allocation of attention during search. For example, nontarget objects that are semantically related to a current target attract attention during visual search even when these objects share no visual features with the target (e.g., Moores, Laiti, & Chelazzi, 2003; Belke, Humphreys, Watson, Meyer, & Telling, 2008; Telling, Kumar, Meyer, & Humphreys, 2010).

The question whether and to what degree object categories are involved in the guidance of attention during visual search is unlikely to be resolved on the basis of behavioural measures alone. Template-based control processes result in attentional biases of visual processing in favour of objects with template-matching features. Because such attentional biases can emerge early and develop gradually over time (see Eimer, 2014, 2015, for reviews), their presence may be revealed by event-related brain potential (ERP) markers of attentional selectivity, which can track these biases on a millisecond-by-millisecond basis. The N2pc component has been employed in many studies of visual attention and visual search as an electrophysiological marker for attentional object selection. The N2pc is an enhanced negativity elicited at posterior electrodes contralateral to the visual hemifield of a candidate target object that is presented among other nontarget objects in visual search displays. It is generated in extrastriate areas of the ventral visual processing stream (Hopf et al., 2000), and

is assumed to reflect the allocation of spatial attention to objects with target-matching properties (e.g., Woodman & Luck, 1999, 2003; Eimer, 1996; Luck & Hillyard, 1994). Although the N2pc often emerges at about 200 ms after search display onset, its onset latency is variable and is determined by how effectively a target object can be discriminated from distractors in the same display. In visual search tasks where target objects are defined by simple visual features such as a particular colour or shape, these targets trigger N2pc components (e.g., Luck & Hillyard, 1994; Eimer, Kiss, & Nicholas, 2011) that are reliably present from about 180 ms post-stimulus. Such results demonstrate that when feature-specific attentional templates for target colours or shapes are activated, template-matching objects trigger rapid spatially selective biases of visual processing. To determine whether object categories play a role in the control of attention, it is important to investigate whether similar N2pc components will also be elicited in response to target objects in search tasks where these targets are defined not by basic visual features, but by the object category to which they belong. If categories cannot guide attention, no N2pc should be found for category-defined targets.

This question was addressed in a recent study from our lab (Nako, Wu, Smith, & Eimer, 2014) where search displays contained line drawings of kitchen and clothing objects. In different blocks, participants either searched for a particular target object (e.g., frying pan; exemplar-based search) or for any of 11 possible objects from the same category (kitchen objects or items of clothing; category-based search). In the exemplar-based search task, target objects triggered large N2pc components that emerged early (at 190 ms post-stimulus), confirming that attention was allocated effectively to target objects when this process was guided by a search template for specific visual target features. Critically, reliable target N2pc components were also found in the category-based search task. However, these N2pcs were smaller in amplitude than those found during exemplar-based search, and were delayed by about 50 ms. These findings suggest that in contrast to previous claims (e.g., Wolfe & Horowitz, 2004), attentional allocation processes can be guided by object categories, and that this type of guidance can result in modulations of relatively early stages of visual processing. On the other hand, they also demonstrate that category-guided attentional selection processes are considerably slower and less efficient relative to the selection of targets that are defined by a set of known visual features.

The goal of the current study was to provide further insights into the similarities and differences of category-based versus exemplar-based attentional control processes during visual search for real-world target objects. Do these two types of attentional guidance processes differ only quantitatively (with category-based guidance operating more slowly than feature-based guidance, e.g., Nako et al., 2014), or are there more fundamental qualitative differences between them? More specifically, we investigated the ability to allocate attention rapidly and in parallel to two different target objects in exemplar-based and category-based search tasks. The distinction between parallel and serial mechanisms is central to theories of visual search, such as Feature Integration Theory (e.g., Treisman & Gelade, 1980) and Guided Search (Wolfe, 1994, 2007), and this dichotomy is usually based on behavioural measures. Serial search is inferred when reaction times (RTs) increase with the number of objects in a search display, while search is described as parallel when target RTs are not affected by display set size. However, the question whether attentional target selection processes operate in a serial or parallel fashion can also be addressed with electrophysiological markers such as the N2pc component.

Evidence for parallel attentional selection processes in tasks where target objects were defined by physical features (a specific colour or shape) comes from a series of recent studies from our lab that used a rapid sequential visual presentation procedure. Two displays that each contained a target and a nontarget object on opposite sides were presented in rapid succession, with stimulus onset asynchronies (SOAs) varied between 10 and 100 ms. To measure N2pc components separately for targets in the first and second display, one of these displays contained a stimulus pair on the horizontal midline and the other a pair on the vertical midline, with display order varied randomly across trials. Because the N2pc is a lateralised component that is only elicited by lateralised target objects but not by targets on the vertical midline, it will only reflect the attentional selection of horizontal but not of vertical targets (see Eimer et al., 2011; Hickey, Di Lollo, & McDonald, 2009; Hickey, McDonald, Theeuwes, 2006; Woodman & Luck, 1999, 2003, for previous N2pc studies that employed this logic). When target objects were defined by their colour (Eimer & Grubert, 2014; Grubert & Eimer, 2015), N2pc components of equivalent size were elicited by horizontal targets in the first and second display. Importantly, when the SOA between the displays was very short (10 ms), these two N2pc components overlapped in time, and their onset latency difference matched the objective onset asynchrony between the two displays. These results

demonstrate that multiple colour-guided attentional target selection processes can be triggered concurrently, with each selection process following its own independent time course. Further studies obtained analogous findings when both target-colour objects appeared simultaneously in a single display (Grubert & Eimer, 2016), when targets were defined by their shape (Jenkins, Grubert, & Eimer, 2016, Exp.1), and also when they were defined by a colour/shape conjunction (Jenkins, Grubert, & Eimer, 2017).

These results demonstrate that feature-based attentional guidance can operate rapidly, flexibly, and in parallel for different feature-defined target objects at different locations in the visual field. The goal of the present study was to find out whether such parallel attentional selection processes are only triggered when targets are defined by basic visual features such as their colour or shape, or whether they are also elicited during search for category-defined targets. If category-based attentional guidance is slower and less efficient than feature-based guidance (e.g., Nako et al., 2014), it may be impossible to allocate attention simultaneously to multiple category-defined target objects that appear in rapid succession. We first tested this hypothesis in a task that employed the same rapid sequential presentation procedure as the studies reported above, except that target objects were now defined by their alphanumeric category (letters or digits; Jenkins et al., 2016, Exp.2). In this task, lateral target objects in the first and second display again triggered temporally overlapping N2pc's, with onset delays that closely matched the objective SOA between the two displays. However, the overall size of these N2pc components was smaller than the N2pc's elicited by shape-defined targets in the same study (Jenkins et al., 2016, Exp.1). Although these findings provide initial evidence for rapid parallel target selection processes with category-defined target objects, the guidance of attention by alphanumeric category might be a special case that is not representative of other types of category-based search. Classifying items as letters or digits is a well-practiced skill, and it has been suggested that alphanumeric category is already extracted during the early parallel processing of visual input (e.g., Duncan, 1980). In line with this hypothesis, numerous studies have shown that letter/digit search is very efficient (Duncan, 1980; Egeth, Jonides, & Wall, 1972), even when the physical similarity between and within these two categories is matched (Dixon & Shedden, 1987).

In the present study, we investigated the guidance of multiple-target selection by object categories in a search task where target categories were more typical of the types of

categories used in everyday search tasks. Participants saw line drawings of real-world target objects from two categories (kitchen objects and items of clothing). The set of objects was identical to the set used by Nako et al., 2014, except that these images were now shown in the context of a rapid sequential presentation procedure (see Figure 1). On each trial, two stimulus pairs (one on the horizontal and the other on the vertical midline) appeared in rapid succession. Each display was presented for 200 ms, and the onset of the first display preceded the onset of the second display by 10 ms. Display sequence (vertical following horizontal or vice versa) varied randomly across trials. Two experimental sessions with different tasks were conducted on separate days with the same participants. In the category-based search task (Experiment 1), targets were defined by their category membership (kitchen or clothing items), and each of the 11 possible objects from the target category was equally likely to appear on each trial. Participants' task was to decide on each trial whether the two successively presented displays contained one or two target-category objects. In one-target (1T) trials, one display contained a target-category and a nontarget-category object, and the other display two nontarget-category objects. In two-target (2T) trials, both displays contained one object from the target and one from the nontarget category. Experiment 2 was identical to Experiment 1, except that search was now exemplar-based, as participants searched for one particular object (e.g., the frying pan).

To assess and contrast the efficiency of feature-guided and category-guided attentional target selection, we measured behavioural performance and N2pc components to lateral target objects in the first and second display, separately for the exemplar-based and category-based search tasks. Since feature-guided attentional object selection can operate concurrently for multiple target objects, the temporal pattern of target N2pc components during exemplar-based search (Experiment 2) should resemble the pattern found previously for colour or shape targets (e.g., Eimer & Grubert, 2014; Jenkins et al., 2016, Exp.1), with temporally overlapping N2pc components of similar size to target objects in the first and second display on 2T trials. Furthermore, performance levels should be high in this task. The critical new question was whether a qualitatively different pattern of behavioural and electrophysiological results would be found for the category-based search task in Experiment 1. On 1T trials, single category-defined target objects in the first or second display should trigger N2pc components in this task, demonstrating category-based attentional guidance. These N2pcs should however emerge later than during exemplar search, confirming that

category-based guidance operates more slowly than feature-based guidance (e.g., Nako et al., 2014). If it is not possible to allocate attention in parallel to two target objects when these objects are defined by their category, clear differences between Experiments 1 and 2 should be found for 2T trials. Performance on these trials should be strongly impaired during category-based search, reflecting the difficulty of attending to and reporting two category-defined targets that appear in rapid succession. If parallel guidance was unavailable, category-based target selection processes would need to operate in a serial fashion, for one target object at a time. This should be reflected by clear differences in the pattern of target N2pc components on 2T trials between Experiment 1 and 2. One possibility is that attention is always allocated to the target object in the first display before it is re-directed to the target in the second display. In this case, the N2pc to this second target should be delayed, without any temporal overlap with the N2pc to the first target. As display durations were short (200 ms), such serial attention shifts may often be too slow to reach the second target before display offset, and this should be reflected by strongly attenuated or entirely absent N2pc components to the second target. Alternatively, attention may be allocated randomly either to the first or second target object on 2T trials, resulting in a strong attenuation of N2pc amplitudes to both targets. Furthermore, such a random selection strategy should also increase the temporal variability of attentional biases across trials, resulting in a delayed onset of target N2pc components. The alternative hypothesis is that similar to feature-defined targets, category-defined target objects can be selected in parallel. In this case, target objects in the first and second display in the 2T trials of Experiment 1 should both trigger temporally overlapping N2pc components of similar size, analogous to what was predicted for the exemplar-based search task (Experiment 2).

Experiment 1

Methods

Participants

Twelve participants, aged 25-38 years ($M = 30.58$ years, $SD = 4.44$), were paid to take part in Experiment 1. Seven participants were female, three were left-handed, and all had normal or corrected-to-normal vision.

Stimuli and Procedure

Stimuli were presented on a 22-inch Samsung wide SyncMaster 2233 LCD monitor (resolution of 1280 x 1024 pixels, 100 Hz refresh rate; 16ms black-to-white-to-black response time, verified using a photodiode). Participants were seated in a dimly lit cabin and viewed the screen from an approximate distance of 100 cm. Stimulus presentation, timing, and response recollection were controlled by a LG Pentium PC operating under Windows XP, using the Cogent 2000 toolbox (www.vislab.ucl.ac.uk/Cogent/) for MATLAB (Mathworks, Inc.). Stimuli were black line drawings (12 clothing objects and 12 kitchen objects; angular size: $4.5^\circ \times 4.5^\circ$; see Figure 1) from the Bank of Standardised Stimuli (Brodeur, Dionne-Dostie, Montreuil, & Lepage, 2010). The same set of stimuli was used previously by Nako et al. (2014). All stimuli were presented at an eccentricity of 4.0° from central fixation (with respect to the object centre) against a white background (see Figure 1). A central black fixation point ($0.2^\circ \times 0.2^\circ$) remained continuously present for the duration of each experimental block.

In each trial, two successive stimulus displays were each presented for 200 ms. Each stimulus display contained two objects on opposite sides of fixation. One stimulus pair was presented on the horizontal midline (left and right of fixation), and the other pair was presented on the vertical midline (above and below fixation). In half of all trials, the horizontal stimulus pair preceded the vertical stimulus pair (horizontal display first: H1 trial). In the other half of trials, this horizontal/vertical display presentation order was reversed (horizontal display second: H2 trial). These two display sequences were randomly intermixed in each block. The onset of the first display preceded the onset of the second display by 10 ms. The interval between the offset of the second display and the onset of the first display on the next trial was 1900 ms.

Participants' task was to find category-defined target objects. Each participant was assigned one of the two possible target categories (clothing or kitchen objects) for the first half of the experiment, and then assigned the other target category for the second half. Six participants searched for kitchen objects first, and six searched for clothing objects first. There were three different trial types: In one-target (1T) trials, one display contained one object

from the target category and one object from the nontarget category, and the other display contained two different nontarget category objects. In two-target (2T) trials, each display contained one object from the target category and one from the nontarget category. Each block also contained infrequent catch trials without targets, where both displays contained two different nontarget category objects. Target and nontarget category objects were randomly selected on each trial, and no objects were repeated within a trial. The horizontal and vertical positions of the target object/objects (left or right; top or bottom) were randomly and independently determined on each trial. Participants were instructed to report the number of target-category objects (one or two) on each trial by pressing one of two purpose-built vertically aligned response keys, and to refrain from responding on catch trials without targets. Response-to-key and hand-to-key mappings were counterbalanced across participants.

The experiment contained 16 blocks of 80 trials. In each block, there were 48 one-target (1T) trials and 24 two-target (2T) trials. 1T trials were twice as likely as 2T trials because on half of these 1T trials, the target appeared on the vertical midline, and no N2pc could be computed. Doubling the number of 1T trials ensured that an equal number of trials was available for computing N2pc components on both types of trials. As a result, trials requiring “one target” responses were twice as likely as trials requiring “two target” responses. In addition, there were 8 catch trials in which no target appeared. Each block contained three 1T trials for each combination of display sequence (H1 trial, H2 trial), target display (first, second) and target position (left, right, top, bottom), and three 2T trials for each combination of display sequence, position of horizontal target (left, right) and position of vertical target (top, bottom). Participants completed one practice block prior to the experiment, and another practice block after 8 experimental blocks (when the target category assignment was changed).

EEG recording and data analyses

The continuous EEG was DC-recorded from 27 scalp electrodes at standard positions of the extended 10/20 system, sampled at a rate of 500 Hz, and digitally low-pass filtered at 40 Hz. No other offline filters were applied. All channels were online referenced to the left earlobe and re-referenced offline to the average of both earlobes. Trials contaminated with artifacts (eye movements exceeding $\pm 30 \mu\text{V}$ in the HEOG channels; eye blinks exceeding ± 60

μV at Fpz; muscular movements exceeding $\pm 80 \mu\text{V}$ in all other channels), and trials with incorrect, anticipatory (faster than 200 ms), very slow (slower than 1500 ms), or missing responses were excluded from EEG analyses. This led to an exclusion of an average of 11.5% of all trials (9.4% and 15.5% of 1T and 2T trials, respectively). For the remaining trials, EEG was segmented into epochs ranging from 100 ms prior to 500 ms after the onset of the first stimulus display, and was baseline corrected relative to the 100 ms interval prior to the onset of the first display. EEG was averaged separately for each of the eight combinations of display sequence (H1, H2), trial type (1T, 2T) and position of horizontal target (left, right; excluding 1T trials where the target appeared on the vertical midline).

N2pc components were quantified on the basis of ERP waveforms measured at lateral posterior electrodes PO7 and PO8. N2pc mean amplitudes were computed within a 100 ms time interval between 220-320 ms after the onset of the horizontal display. This time window is later than the typical 200-300 ms N2pc time interval used in search tasks with feature-defined targets. It was informed by the N2pc results found in our previous study of category-based search that employed the same set of stimuli (Nako et al., 2014), and showed delayed N2pcs when targets were defined by their category. The same time window was employed for 1T and 2T trials. N2pc onset latencies were measured based on difference waveforms, computed by subtracting ipsilateral from contralateral ERPs at PO7 and PO8. Onset latencies were determined with a jackknife-based procedure (Miller, Patterson, & Ulrich, 1998; Ulrich & Miller, 2001). Twelve grand-average difference waves were computed for each experimental condition, each excluding one different participant from the original sample. N2pc onset latency was defined as the point in time when each subsample difference wave reached an absolute onset amplitude of $-1 \mu\text{V}$. Differences in N2pc onset latencies between different combinations of display sequence and number of targets were assessed with repeated-measures ANOVAs and *t*-tests, with *F*- and *t*-values corrected according to the formulas described by Ulrich and Miller (2001) and Miller et al. (1998), respectively. The corrected statistical values are indicated with F_c and t_c , respectively. All *t*-tests were two-tailed and Bonferroni corrected where necessary. To measure effect sizes, Cohen's *d* (Cohen, 1988) was computed for all *t*-tests, and partial eta-squared (labelled η_p^2) was computed for all ANOVAs. In order to correct individual group means and standard deviations of jackknifed samples, the N2pc latency group means obtained through the jackknife procedure were fed into repeated-measures ANOVAs from which the error variance was corrected according to

the formula described by Ulrich and Miller (2001). For this reason, effect sizes from N2pc latency analyses are reported as η_p^2 .

Results

Behavioural performance

The removal of trials with anticipatory or exceedingly slow RTs resulted in the exclusion of 1.1% of all trials. A repeated-measures ANOVA with the factors trial type (1T versus 2T trials) and display sequence (H1 versus H2 trials) was run separately for RTs on trials with correct responses and for error rates. RTs were numerically faster on 2T trials relative to 1T trials (855 ms versus 878 ms), but this difference was not significant (main effect of trial type, $F(1,11) = 2.10$, $p = .175$, $\eta_p^2 = .16$). There was also no effect of display sequence on RTs, $F(1,11) = .04$, $p = .842$, $\eta_p^2 = .00$, and no interaction between these two factors, $F(1,11) = .44$, $p = .175$, $\eta_p^2 = .04$. Errors were more frequent in 2T relative to 1T trials (9.1% versus 3.1%; main effect of trial type: $F(1,11) = 39.41$, $p < .001$, $\eta_p^2 = .78$). There was no effect of display sequence on error rates, $F(1,11) = 1.50$, $p = .247$, $\eta_p^2 = .12$, and no interaction, $F(1,11) = .85$, $p = .375$, $\eta_p^2 = .07$. On catch trials, the rate of False Alarms was 4.9%.

N2pc components

Figure 2 (left and middle panels) shows ERPs at posterior electrodes PO7/8 contralateral and ipsilateral to the side of the horizontal target for trials where this target appeared in the first display (H1 targets) or in the second display (H2 targets). The right panel of Figure 2 shows N2pc difference waveforms obtained by subtracting ipsilateral from contralateral ERPs for H1 and H2 targets. ERPs are shown separately for 1T (top) and 2T (bottom) trials. It is obvious that clear N2pc components were elicited not only on 1T trials where a single category-defined target object was presented, but also on 2T trials by horizontal target objects that were accompanied by another vertical category-defined target object in the other display. In addition, N2pc components of similar size were elicited by H1 and H2 targets. A repeated-measures ANOVA of N2pc mean amplitudes with the factors trial type (1T versus 2T), display sequence (H1 target versus H2 target), and laterality (electrode contralateral versus ipsilateral to the side of the horizontal target) confirmed these observations. There was a main effect of laterality, $F(1,11) = 41.71$, $p < .001$, $\eta_p^2 = .79$,

demonstrating that N2pc components were reliably triggered by category-defined horizontal target objects. Display sequence did not interact with laterality, $F(1,11) = 1.00$, $p = .340$, $\eta_p^2 = .08$, indicating that N2pc components of similar size were elicited by horizontal target objects in the first and second display. However, there was an interaction between trial type and laterality, $F(1,11) = 8.58$, $p < .05$, $\eta_p^2 = .44$, as N2pc components were larger on 1T trials than on 2T trials (mean amplitudes $-1.56 \mu\text{V}$ and $-1.15 \mu\text{V}$, respectively). However, follow up t -tests comparing contra- with ipsilateral activity in response to H1 and H2 targets separately for 1T and 2T trials confirmed that N2pc components were reliably present not only on 1T trials but also on 2T trials, all $t(11) > 4.39$, $p < .01$, $d > .24$. Mean N2pc amplitudes for H1 and H2 targets were $-1.65 \mu\text{V}$ and $-1.47 \mu\text{V}$ on 1T trials, and $-1.20 \mu\text{V}$ and $-1.10 \mu\text{V}$ on 2T trials.

A repeated-measures ANOVA was run on N2pc onset latency values determined with a jackknife-based procedure (see Methods) with the factors trial type and display sequence. Even though there was a tendency for N2pc components to emerge earlier on 1T trials than on 2T trials (234 ms versus 250 ms), the main effect of trial type only approached significance, $F_c(1,11) = 3.42$, $p = .092$, $\eta_p^2 = .24$. There was no main effect of display sequence, $F_c(1,11) = .00$, $p = .926$, $\eta_p^2 = .00$, indicating that there was no onset latency difference between N2pc components to H1 and H2 targets that reflected the objective 10 ms SOA between the two displays.

Experiment 2

Methods

Participants

The same twelve participants that took part in Experiment 1 were tested in Experiment 2. The two experiments took place in separate sessions on different days.

Stimuli and Procedure

Stimuli were identical to Experiment 1. Participants were now assigned a specific target object from one category (one particular exemplar of clothing or kitchen objects) for the first half of the experiment, and a different target object from the other category for the

second half of the experiment. Six participants searched for a specific kitchen object first, and the other six searched for a specific clothing object first. The assignment of task order across participants was random, and independent of the individual task order assignment in Experiment 1. To ensure that target selection in Experiment 2 was exemplar-based rather than category-guided, all target objects were accompanied by a nontarget object from the same category on the opposite side. On 1T trials where one of the two displays contained two nontarget objects, one of these objects was drawn from the same category as the target and the other from the other category. Objects were randomly selected on each trial, and no nontarget objects were repeated within a trial. All other aspects of stimulus presentation and procedure were identical to Experiment 1.

EEG recording and data analyses

EEG recording, analysis and trial exclusion procedures were identical to Experiment 1. On average 11.5% of all trials were excluded from analysis (10.9% and 12.6% of 1T and 2T trials, respectively). For all remaining trials with horizontal targets, EEG was averaged separately for each of the eight combinations of display sequence (H1, H2), trial type (1T, 2T) and position of horizontal target (left, right). Based on the results of our previous study (Nako et al., 2014), target N2pc components were expected to emerge earlier in the exemplar-based selection task of Experiment 2 than in the category-based task of Experiment 1. For this reason, an earlier N2pc time window (200-300 ms after the onset of the horizontal display) was employed in Experiment 2.

Results

Behavioural performance

Exclusion of anticipatory and slow responses removed less than 0.1% of trials. Mean RTs on trials with correct responses were 515 ms on 1T trials and 526 ms on 2T trials. A repeated-measures ANOVA on RTs with the factors trial type (1T versus 2T trials) and display sequence (H1 versus H2 trials) revealed no main effects and no interaction between factors, all $F(1,11) < 1.79$, $p > .256$, $\eta_p^2 < .14$. The same analysis of error rates also revealed no main effects and no interaction, all $F(1,11) < 3.84$, $p > .076$, $\eta_p^2 < .26$ (error rates on 1T and 2T trials: 1.2% and 2.9%). The False Alarm rate on catch trials was 1.1%.

N2pc components

Figure 3 shows ERPs for trials with horizontal targets, separately for H1 and H2 targets on 1T and 2T trials, with the corresponding N2pc difference waveforms. Clear N2pc components were triggered by H1 and H2 targets in both types of trials. As expected, these N2pcs to visually defined exemplar targets were larger in amplitude and emerged earlier than the N2pcs to category-defined target objects in Experiment 1 (Figure 2; see below for formal comparisons). A repeated-measures ANOVA examined mean N2pc amplitudes with the factors trial type (1T versus 2T), display sequence (H1 versus H2), and laterality (electrode contralateral versus ipsilateral to the side of the horizontal target). A main effect of laterality, $F(1,11) = 44.47, p < .001, \eta_p^2 = .80$, confirmed the presence of N2pc components in response to horizontal targets. There was an interaction between trial type and laterality, $F(1,11) = 9.33, p < .05, \eta_p^2 = .46$. In contrast to Experiment 1, N2pc amplitudes on 1T trials were now smaller than on 2T trials (mean amplitudes $-2.46 \mu\text{V}$ and $-3.21 \mu\text{V}$, respectively). The interaction between display sequence and laterality approached significance, $F(1,11) = 4.13, p = .067, \eta_p^2 = .27$, reflecting a tendency towards larger N2pc components for H2 targets (see Figure 3). There was no three-way interaction between trial type, display sequence, and laterality, $F(1,11) = .32, p = .584, \eta_p^2 = .03$. Follow up *t*-tests comparing contralateral with ipsilateral ERPs in response to H1 and H2 targets, separately for 1T and 2T trials, confirmed that reliable N2pc components were present in all four task conditions, all $t(11) > 5.28, p < .001, d > .51$. Mean amplitudes in 1T trials were $-2.37 \mu\text{V}$ and $-2.55 \mu\text{V}$ for H1 and H2 trials, respectively. In 2T trials, these mean amplitudes were $-3.04 \mu\text{V}$ and $-3.38 \mu\text{V}$.

For N2pc onset latencies, a repeated-measures ANOVA with the factors trial type and display sequence revealed no main effect of trial type, $F_c(1,11) = 1.50, p = .247, \eta_p^2 = .12$ and no main effect of display sequence, $F_c(1,11) = 3.09, p = .107, \eta_p^2 = .22$. However, there was an interaction between these two factors, $F_c(1,11) = 5.36, p < .05, \eta_p^2 = .33$. There was no N2pc onset latency difference between H1 and H2 targets on 1T trials (210 ms and 212 ms), $t_c(11) = .52, p = .612, \eta_p^2 = .02$. In contrast, the N2pc to H2 targets was delayed by 12 ms relative to the N2pc to H1 targets on 2T trials (201 ms versus 213 ms), $t_c(11) = 2.35, p < .05, \eta_p^2 = .33$, mirroring the objective 10 ms SOA between the two successive displays.

Comparisons across experiments

Because the same participants were tested in Experiments 1 and 2, additional within-participant comparisons of behavioural performance and N2pc components were conducted to assess differences between the category-based and exemplar-based selection of one or two target objects.

Behavioural performance. Repeated-measures ANOVAs with the factors trial type (1T versus 2T trials), display sequence (H1 versus H2 trials) and selection task (category selection in Experiment 1 versus exemplar selection in Experiment 2) were conducted for RTs and error rates. As expected, RTs were much slower for the category-based selection task (Experiment 1) than with exemplar-based selection in Experiment 2 (866 ms versus 521 ms; main effect of selection task: $F(1,11) = 166.03$, $p < .001$, $\eta_p^2 = .94$). There were no significant interactions involving the factor selection task for RTs, all $F(1,11) < 2.93$, $p > .115$, $\eta_p^2 < .21$. Errors were more frequent during category selection than during exemplar selection (6.2% versus 2.1% in Experiments 1 and 2, respectively; main effect of selection task: $F(1,11) = 15.90$, $p < .01$, $\eta_p^2 = .59$). Apart from an interaction between selection task and trial type, $F(1,11) = 10.33$, $p < .01$, $\eta_p^2 = .48$, reflecting the fact that errors were more frequent on 2T relative to 1T trials in Experiment 1 but not in Experiment 2, no other interactions involving the factor selection task were present for error rates, all $F(1,11) < 1.67$, $p > .223$, $\eta_p^2 < .14$.

N2pc components. N2pc components were much larger when targets were specific exemplar objects (Experiment 2; mean amplitude: $-2.84 \mu\text{V}$) than when they were defined by object category (Experiment 1; mean amplitude: $-1.36 \mu\text{V}$). This difference was confirmed by an interaction between selection task and laterality, $F(1,11) = 10.97$, $p = .01$, $\eta_p^2 = .50$. There was also a three-way interaction between selection task, trial type, and laterality, $F(1,11) = 15.44$, $p < .01$, $\eta_p^2 = .58$, reflecting the fact that N2pc components were larger on 1T than on 2T trials in Experiment 1, but larger on 2T relative to 1T trials in Experiment 2. N2pc components were also triggered more rapidly by exemplar targets in Experiment 2 than by category-defined targets in Experiment (209 ms versus 242 ms post-stimulus). This was confirmed by a significant main effect of selection task in the analysis of N2pc onset latencies across both experiments, $F_c(1,11) = 19.65$, $p < .01$, $\eta_p^2 = .64$.

Discussion

The question whether object categories are able to guide selective attention during visual search remains disputed, and existing behavioural evidence is inconclusive (e.g., Malcolm & Henderson, 2009; Moores et al., 2003). In the current study, we investigated the speed and the parallel versus serial nature of category-based and exemplar-based attentional target selection processes with electrophysiological markers. We employed a task where two successive displays were separated by an SOA of 10 ms, and either one or both displays contained a target object. In Experiment 1, participants had to find one or two category-defined target objects (one of 11 possible kitchen or clothing items) that appeared together with a nontarget-category distractor in the same display. Experiment 2 used identical procedures, except that one specific object now served as target, so that attentional selection processes could be based on known physical target features. In both experiments, N2pc components to lateral target objects were measured as electrophysiological markers of category-guided versus feature-guided target selection processes.

Previous N2pc studies that used analogous rapid sequential target presentation procedures in tasks where targets were defined by a particular colour or shape (e.g., Eimer & Grubert, 2014; Jenkins et al., 2016) found temporally overlapping N2pcs of similar size for lateral target objects in the first and second display, demonstrating that feature-guided attentional selection processes were triggered concurrently and independently for different target objects in the visual field. Experiment 1 investigated whether such parallel target selection processes would also be elicited in a task where target objects were not defined by specific features, but by their category, or whether qualitatively different serial selection mechanisms operate during search for category-defined targets. The temporal pattern of N2pc components observed in Experiment 1 was very similar to the pattern found in previous experiments with feature-defined targets. On 2T trials where both displays contained a target object, lateral targets in the first and second display (H1 and H2 targets) both triggered clear N2pc components that overlapped in time and did not differ significantly in terms of their amplitudes, suggesting that attention was allocated concurrently to both target objects, in spite of the fact that targets and nontargets could only be distinguished on the basis of their category. Importantly, the temporal pattern of N2pc components observed in Experiment 1

during category-based search was similar to the pattern found in the exemplar-based search task of Experiment 2. Here, H1 and H2 targets again elicited temporally overlapping N2pc components, indicating that they were selected concurrently. This confirms earlier observations in tasks with simple geometrical stimuli and colour- or shape-defined targets, and shows that parallel feature-guided target selection processes also operate in contexts where targets and distractors are more complex real-world objects. Overall, these results show that there are no fundamental qualitative differences in the guidance of attention towards feature-defined and category-defined target objects. When these objects appear in rapid succession at different locations, they can be selected in parallel, regardless of whether these selection processes are controlled by feature or by category templates.

While the overall pattern of N2pc components was similar in Experiment 1 and 2, there were also systematic differences. Target N2pc components emerged about 30 ms earlier and N2pc amplitudes were about twice as large during exemplar-based search (Experiment 2) relative to category-based search (Experiment 1). Furthermore, RTs were much faster in the exemplar-based search task. As all participants completed the category-based search task (Experiment 1) prior to the exemplar-based task (Experiment 2), this RT difference could to some degree reflect attention-independent practice effects, such as familiarity with the stimuli and with spatial and temporal task parameters. However, such carry-over effects cannot account for the fact that RTs were more than 300 ms faster in Experiment 2. In line with previous behavioural and electrophysiological findings, the RT and N2pc differences between Experiments 1 and 2, and in particular the fact that target N2pc components were delayed in Experiment 1, show that the guidance of attention by physical target features is more effective than the guidance of categories (see also Yang & Zelinsky, 2009; Nako et al., 2014). In addition, the onset of target N2pc components elicited on 2T trials in Experiment 2 was sensitive to the objective 10 ms SOA between the two displays. The N2pc to H1 targets preceded the N2pc to H2 targets by 12 ms, in line with similar observations for colour-guided search (e.g., Eimer & Grubert, 2014). In contrast, there was no such N2pc onset latency difference between H1 and H2 targets in Experiment 1. This presumably reflects increased temporal variability in the onset of category-guided attentional selection processes across trials (see also Jenkins et al., 2016, Exp.2, for an analogous absence of N2pc latency differences during the rapid parallel selection of two target objects that were defined by their

alphanumeric category). This factor may also be partially responsible for the fact that target N2pc amplitudes were considerably smaller in Experiment 1 relative to Experiment 2.

Although the N2pc results found in Experiment 1 suggest that category-based attentional control mechanisms can operate in parallel for different objects at different locations in the visual field, alternative interpretations have to be considered. One possibility is that the selection of two successively presented category-defined targets operates serially, and that attention is always first directed to the target in the first display before it is re-allocated to the second target. In this case, the N2pc to H2 targets should have been strongly attenuated and delayed relative to the N2pc to H1 targets on 2T trials in Experiment 1, which was clearly not the case. Alternatively, participants may have randomly selected either the first or the second target on any given 2T trial. In this case, N2pc components to H1 and H2 target should both be strongly attenuated (by 50%) on 2T relative to 1T trials where only a single target object was presented. N2pc components to H1 and H2 targets in Experiment 1 were indeed reliably smaller on 2T trials relative to 1T trials.¹ However, this attenuation was considerably smaller ($-1.15 \mu\text{V}$ versus $-1.56 \mu\text{V}$, reflecting a reduction of 25%) than predicted by a random single-target selection account. This strongly suggests that both targets were selected concurrently on at least a substantial proportion of all 2T trials, which is sufficient to conclude that parallel category-based attentional guidance is possible. It should also be noted that participants incorrectly reported the presence of a single target on only 9% of all 2T trials in Experiment 1. These error trials, which are likely to be the result of a failure to attend to both target objects, were not included in the N2pc analysis. On trials with correct responses, there were no significant RT differences between 1T and 2T trials (and even a trend towards faster RTs on 2T trials), suggesting that participants were equally confident in reporting two targets as compared to a single target. Given these observations, it is very unlikely that only one of the two target objects was selected on all 2T trials in Experiment 1. Alternatively, the reduction of N2pc amplitudes on 2T trials in Experiment 1 may be the result of competitive interactions between two simultaneously activated category-based target selection processes.

¹ Unexpectedly, the opposite pattern was found in Experiment 2 during exemplar-based search, with larger N2pc amplitudes on 2T relative to 1T trials. This could be due to the fact that on 2T trials, two physically identical target objects appeared in rapid succession on the horizontal and vertical midline. Instead of producing interference, the concurrent selection of identical objects might facilitate attentional biases at each target location. This possibility needs to be investigated more systematically in future research.

In Experiment 2, target objects were always accompanied by a nontarget from the same category in the same display, to ensure that the guidance of target selection was exemplar-based. Even though categories had to be ignored, it is possible that the category of the current target object was still included in the search template. Initial evidence for an automatic activation of object categories during exemplar-based search was found by Nako et al. (2014). In this experiment, target-absent displays could contain a “foil” object (i.e., a nontarget object that belonged to the same category as the target). These foils triggered a small but reliable N2pc, indicating that they were able to attract attention. To assess whether a template for the target category was also activated during the exemplar-based task of Experiment 2, we computed N2pc components elicited on 1T trials with a vertical target/nontarget pair and a horizontal pair of nontarget objects. Because one of the horizontal nontargets matched the category of the current target, any residual activation of this category should result in an N2pc to this category-matching object. As can be seen in Figure 4 (which shows ERP waveforms collapsed across H1 and H2 trials, time-locked to the onset of the horizontal display on these trials), this was indeed the case. An analysis of ERPs elicited at PO7/8 in the 200-300 ms post-stimulus time window confirmed that a small but reliable N2pc was elicited by category-matching distractors (main effect of laterality: $F(1,11) = 5.77, p < .05, \eta_p^2 = .34$), demonstrating that these objects attracted attention on at least some trials. This provides new evidence that when observers search for a specific real-world target object, the category of this object is activated even when this is not helpful for dissociating targets and distractors. Although this activation was involuntary, it may not be entirely automatic: Because all participants were first tested in the category-based search task of Experiment 1, prior practice with category-based selection might have facilitated the activation of category templates in Experiment 2 where they were no longer task-relevant. The question whether such involuntary activation processes can also be triggered without being primed by a prior category selection task will need to be investigated in future research.

If attention can be allocated independently and concurrently to two category-defined target objects, as suggested by the present N2pc results, the question arises how this type of category-guided attentional control might be implemented at the neural level. The N2pc itself represents visual processing biases in extrastriate cortex that are elicited in a spatially selective fashion by target objects. These biases are likely to be triggered by top-down input from higher-level attentional control regions that signal the location of objects that match the

current target template. When targets are defined by their category, as in Experiment 1, attentional control needs to include brain regions that are sensitive to object categories. Several areas in the inferior temporal cortex have been found to be involved in object categorisation (e.g., Miller, Nieder, Freedman, & Wallis, 2003), and these areas are known to be directly linked to the ventrolateral prefrontal cortex (e.g., Kravitz, Saleem, Baker, Ungerleider, & Mishkin, 2013). Thus, the attentional biases for category-defined target objects reflected by N2pc components could be the result of signals that are initially generated in category-sensitive temporal areas, are transmitted to prefrontal attentional control regions, and then via recurrent feedback loops back to visual cortex. While the exact details of their cortical implementation remain to be determined, the current results demonstrate that category-selective control processes are involved in the guidance of attention. Although they operate more slowly than the processes involved in the guidance of attention by visual target attributes, they can still be activated concurrently for multiple category-defined target objects at different locations.

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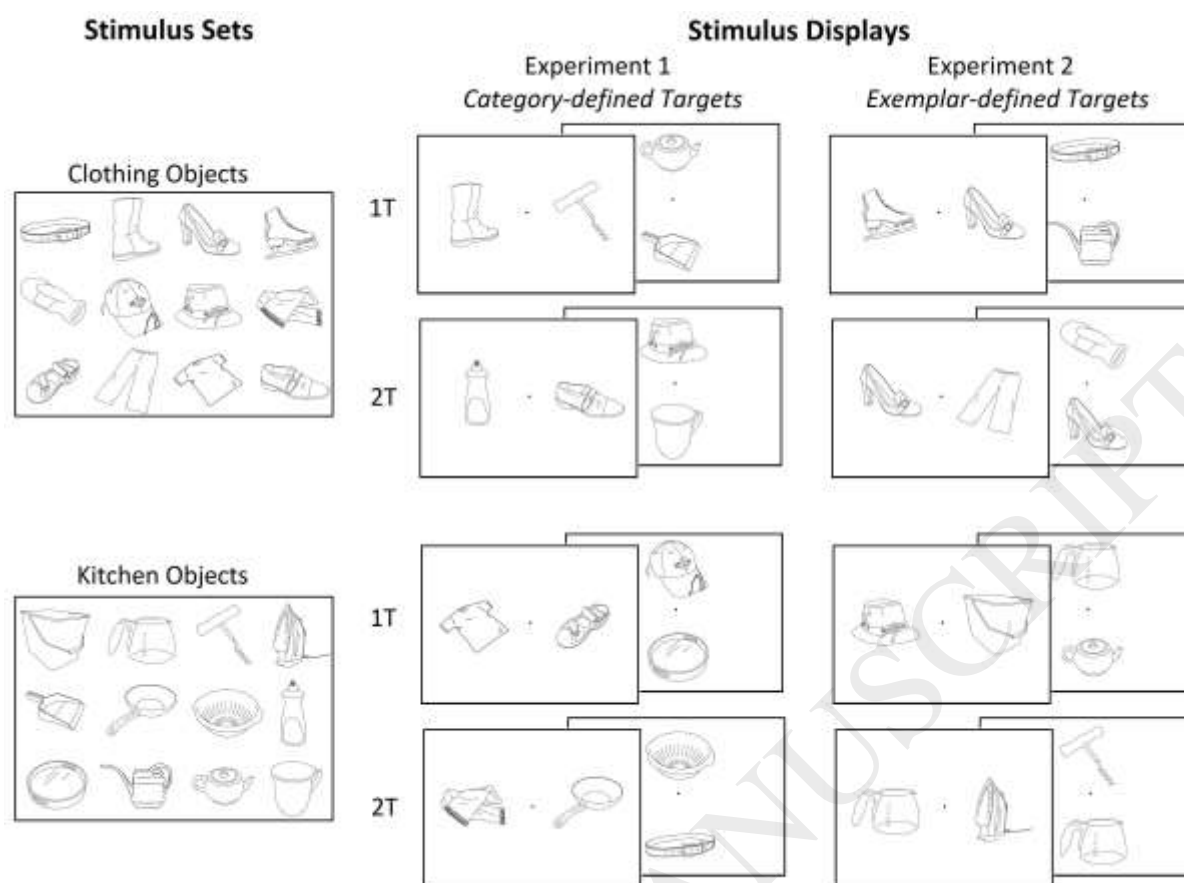


Figure 1. Schematic illustration of the stimulus sets (left) and display sequences in Experiments 1 and 2 (right). On each trial, two displays were presented for 200 ms each, separated by a 10 ms SOA. One display contained a pair of objects on the horizontal midline, the other a pair on the vertical midline. Display sequence (horizontal → vertical, as shown here, or vertical → horizontal) varied randomly between trials. In Experiment 1, targets were defined by their category (items of clothing or kitchen objects). In Experiment 2, one specific object served as the target. On each trial, a target object was presented either in one of the two displays (1T trials) or in both displays (2T trials), and participants' task was to report the number of targets (one or two).

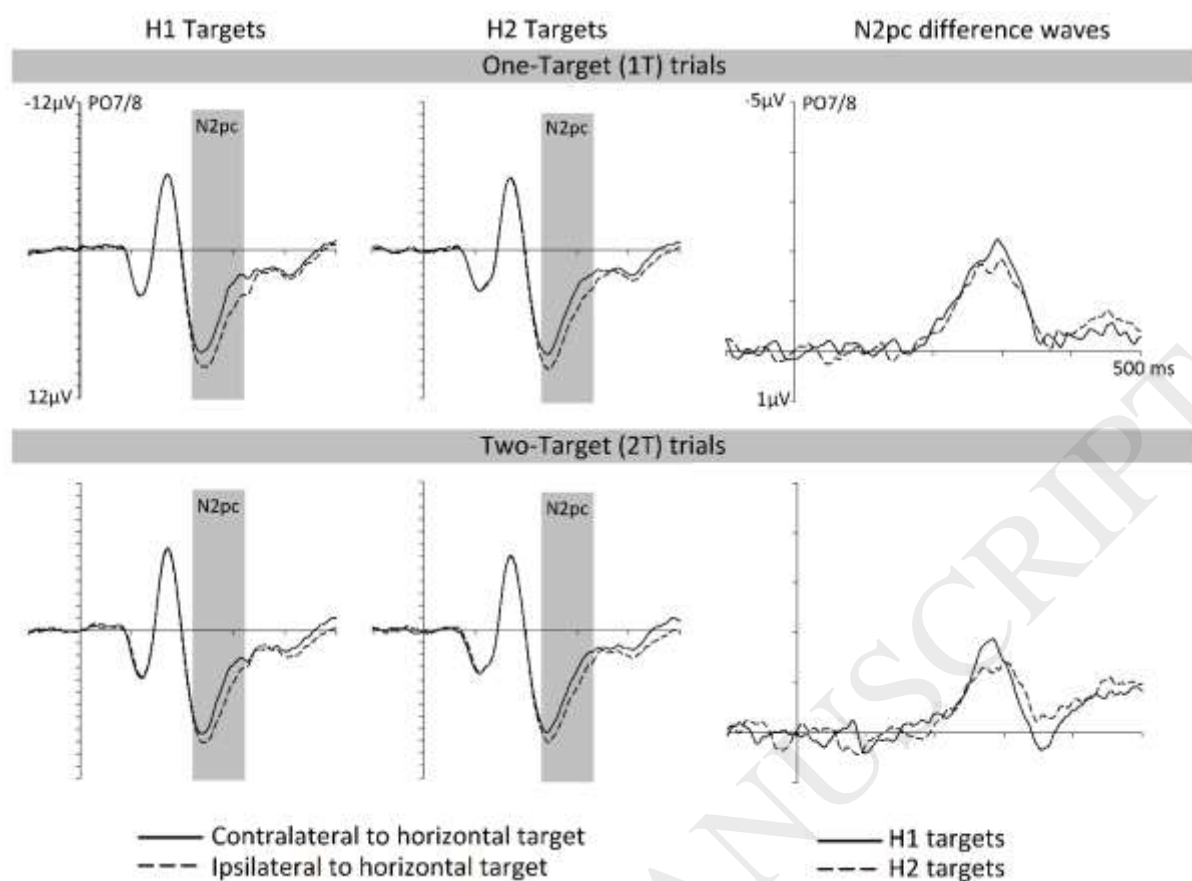


Figure 2. N2pc results in Experiment 1. The left and middle panels show grand-averaged ERP waveforms measured in the 500 ms interval after the onset of the first search display at posterior electrodes PO7/PO8. ERPs elicited contralateral and ipsilateral to a horizontal target object in the first display (H1 targets) or second display (H2 targets) are shown separately for one-target trials and two-target trials. The right panels show corresponding N2pc difference waveforms obtained by subtracting ipsilateral from contralateral ERPs. The grey areas mark the N2pc analysis windows for H1 and H2 targets.

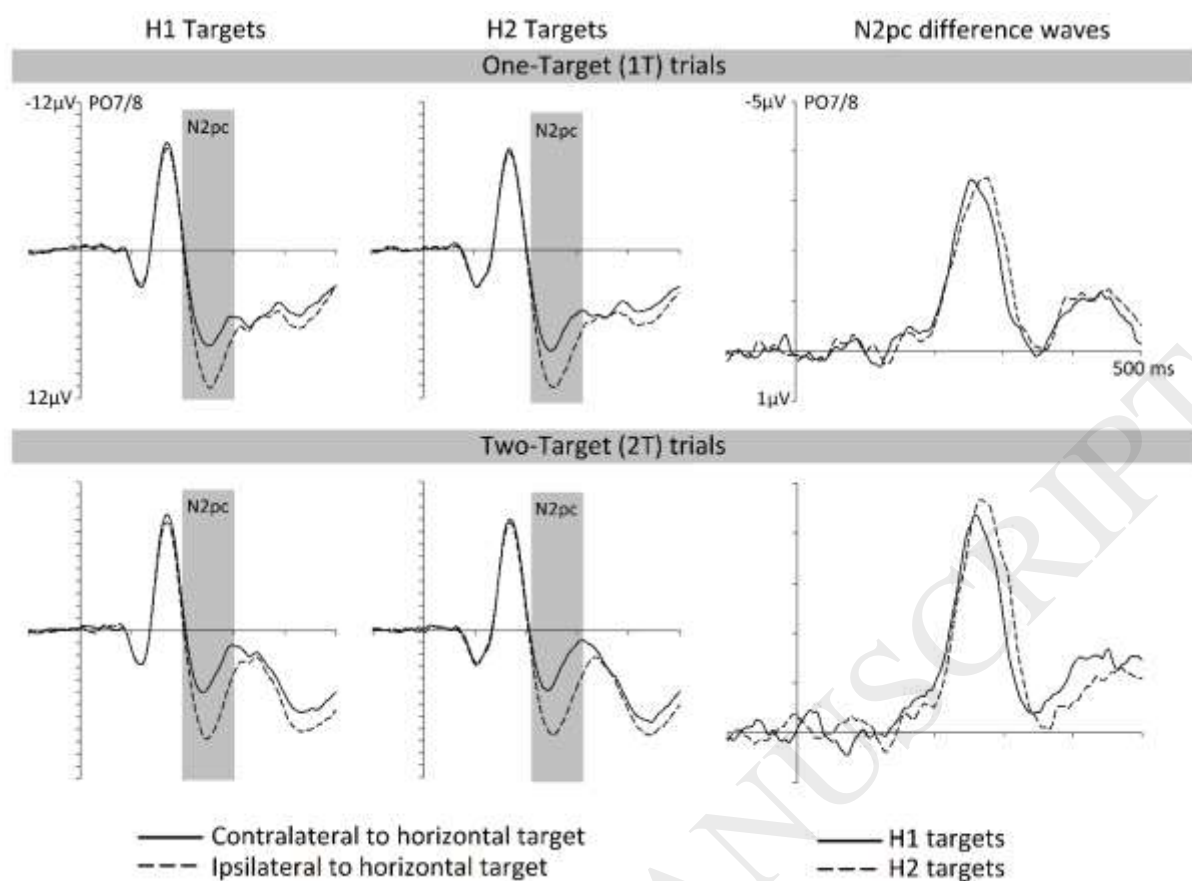


Figure 3. N2pc results in Experiment 2, shown in an identical fashion to Experiment 1. ERPs obtained at PO7/8 in the 500 ms interval after the onset of the first search display in response to H1 and H2 targets are shown together with the corresponding N2pc difference waveforms. The grey areas mark the N2pc analysis windows for H1 and H2 targets.

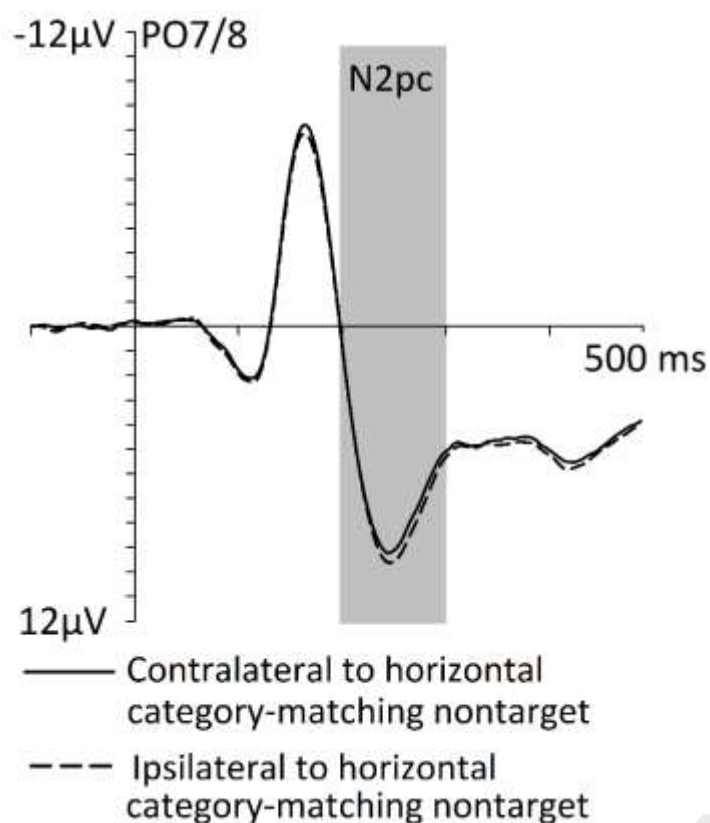


Figure 4. ERPs elicited in Experiment 2 at electrodes PO7/8 on 1T trials in response to displays with a lateral nontarget object that matched the category of the current target and a lateral category-nonmatching nontarget object on opposite sides. ERPs elicited contralateral and ipsilateral to the category-matching nontarget are shown separately. The grey area marks the N2pc analysis window.